This article studies the effect of liability rules in cases in which a single injurer makes sequential decisions. Our work is motivated in large part by our interest in the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA),\(^1\) also known as the federal Superfund statute. Under CERCLA, liability for the cleanup of hazardous waste sites and for damage to natural resources falls on the owner of the hazardous waste site, certain prior owners of the site, and transporters and generators of the waste.\(^2\)

Because the legal regime appears to apportion the bulk of the damages to generators of hazardous waste,\(^3\) the incentives that liability rules transmit to generators form the focus of this article. Generators typically send wastes to a site on an ongoing basis. Thus, analyzing the incentives of liability rules requires a model of sequential decision making, in which a generator's decision to send wastes to a site at any particular time is dependent on the prior stream of wastes that it has already sent to the site as well as on the wastes that it intends to send to that site in the future.

A full treatment of this subject would not only model an actor's decisions as sequential but would also study the implications of the presence of multiple generators at a single site. Instead, to abstract the features

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\(^*\) Professors of Law, New York University. Marcel Kahan and participants at law and economics workshops at the University of Chicago Law School, Georgetown University Law Center, and Stanford Law School gave us valuable comments. The generous financial support of the Filomen D'Agostino and Max E. Greenberg Research Fund at the New York University School of Law is gratefully acknowledged.


\(^2\) Id. at § 9607 (a).

that result from the sequential nature of the decisions, we study here the actions of a single actor.

Another feature of Superfund cases is the potential insolvency of the actors. The average cleanup cost of a Superfund site is currently $25,000,000;4 some cleanups cost more than $100,000,000.5 Even though the cost of cleanup is generally apportioned among many actors, individual actors are often responsible for large amounts. Thus, actors are often unable to pay their share of the damages. We here restrict attention to the incentives of liability rules on actors who are infinitely solvent; we hope subsequently to address the more complex problems posed by potential insolvency.

This article builds on our prior work. We first studied the incentives of liability rules on joint, infinitely solvent tortfeasors acting in a single period.6 We then relaxed the assumption of infinite solvency and studied the incentives of liability rules on potentially insolvent tortfeasors.7 In this article, we further articulate the model by providing for sequential decisions but also simplify it by dealing only with a single, solvent actor.

Our work on infinitely solvent tortfeasors acting in a single period concluded that negligence rules are efficient under joint and several liability as long as the standards of care for each of the actors are set at the socially optimal level but that negligence rules are not generally efficient in the absence of joint and several liability.8 We also determined that strict liability rules are not efficient regardless of whether there is joint and several liability.9

Next, in our article on potential insolvency among joint tortfeasors acting in a single period, we determined that it is not possible to draw any general conclusion about whether, on efficiency grounds, negligence is preferable to strict liability, or whether joint and several liability is preferable to nonjoint (several only) liability.10 The relative efficiency of these rules depends on the characteristics of the joint tortfeasors: the

8 See Kornhauser & Revesz, supra note 6, at 846–55.
9 See id. at 856–58.
10 Kornhauser & Revesz, supra note 7, at 646–49.
benefits that they derive from the economic activity, the costs that their activities impose on society, and their levels of solvency.

In this study of sequential decision making, we conclude that, for solvent actors, strict liability leads to the maximization of social welfare. We also analyze the conditions under which an actor would increase or decrease the amount of waste dumped in subsequent periods.

We then distinguish various types of negligence rules. Specifically, we contrast “forgiving” and “unforgiving” rules. Under a forgiving rule, an actor’s negligence in one period does not make it liable for accidents that occur in subsequent periods in which it is not negligent. Under an unforgiving rule, a previously negligent actor is liable for accidents that occur in subsequent periods in which the actor is not negligent. We then analyze three plausible negligence rules. We show that the first of these rules produces underdeterrence and the remaining two rules lead to the maximization of social welfare. We then classify these two welfare-maximizing rules—one as forgiving, the other as unforgiving—and discuss their relative merits.

In analyzing all the rules, we focus primarily on a model in which an actor makes sequential decisions over two periods. We also consider, however, an infinite-period problem. We can thus determine the extent to which our conclusions depend on “end-period” effects.

While the example used throughout the article concerns the disposal of hazardous wastes, the analysis has a broader scope. Problems of sequential decision making are not restricted to the hazardous waste context. For example, a manufacturing firm deciding the level of toxic hazard to which its workers should be exposed faces analogous issues. At any given time, the firm’s decision will be a function of the past exposure of the workers as well as an estimate of future exposure. Similar problems arise in the maintenance decisions of some capital goods such as airplanes.

The article is organized as follows. Section I sets forth the model that underlies our analysis. Section II analyzes the effects of strict liability. Section III analyzes the effects of the several plausible negligence rules. A mathematical appendix to a companion working paper provides proofs to various claims made informally in the text.

11 Even though CERCLA is a strict liability statute, we analyze the effects on the actor’s incentives of both negligence and strict liability because it is relevant to inquire whether the choice of strict liability was wise. See Kornhauser & Revesz, supra note 6, at 836 n. 27.

I. THE MODEL

In our model, a single, infinitely solvent actor generates hazardous wastes and dumps them at a landfill. The actor benefits from this dumping because the wastes are the by-product of profitable economic activity. In each of the two periods, the actor makes decisions about the level of wastes to generate. At the end of each period, there can be a release of hazardous wastes into the environment. The periods are defined by fixed time intervals.

Our discussion distinguishes between dumping and a release. Dumping involves sending hazardous wastes to a disposal site. We assume that the site complies with the appropriate ex ante regulatory requirements and is licensed to accept such wastes. Dumping, therefore, does not impose an immediate social cost. Even if the site is properly lined and maintained, however, there is the possibility that at some time in the future the wastes will migrate to the surrounding soil and even to the groundwater. Such migration constitutes a release.

The loss caused by such a release is equal to the cost of the cleanup and any damage to natural resources. This loss is a social loss because it does not fall directly on the dumper absent a legal provision shifting the liability. Under strict liability, the actor is responsible for the full loss. Under negligence, in contrast, it is responsible for the full loss only if it violates the standard of care imposed by the legal regime; otherwise, it is liable for no loss at all.

We label as $x$ the amount of waste that the actor chooses to dump in period 1. In period 2, the actor’s decision of the level of waste to dump depends on whether there was a release at the end of period 1. We label as $y$ the amount of waste the actor chooses to dump in period 2, given that there has been no release in period 1. In turn, we label as $z$ the amount of waste the actor chooses to dump in period 2, given that there

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13 Supra note 1, at § 9607(a).

14 The standard of care in our example is the maximum permissible amount of waste that an actor can dump without incurring responsibility for the loss. Under this formulation, more dumping implies less care. In a sense, what is being chosen here is an activity level rather than a level of care. However, neither the model nor the results are conceptually different from the formulation in which the actor chooses more traditional levels of care.

In a prior article, we distinguished between full liability and partial liability rules. Under a full liability rule, when a single actor is negligent, it is responsible for the full social loss. Under a partial liability rule, the actor is responsible only for losses that would have been prevented through due care. See Kornhauser & Revesz, supra note 6, at 837–40. Here, we focus on full liability rules; we consider some features of partial liability rules at notes 31, 34, and 44 infra.

15 We assume that all of the wastes generated in one period are dumped in that period.
has been a release in period 1. Under rules of negligence, the standards of care that correspond to the choices \( x, y, \) and \( z \) are \( \hat{x}, \hat{y}, \) and \( \hat{z}, \) respectively.

At the end of period 1, the probability of a release is \( p_1. \) If there is a release at the end of period 1, the probability of a release at the end of period 2 is also \( p_1. \) If there is no release at the end of period 1, the probability of a release at the end of period 2 is \( p_2. \) To capture the idea that the probability of a release increases with the time that the wastes remain in a landfill, we assume that \( p_2 \) is greater than \( p_1. \)

The benefits that the actor receives in each period from dumping a level of wastes \( r \) is \( B(r); \) we assume that this function is concave. The cleanup cost for \( r \) in the event of a release is \( L(r); \) we assume that this function is convex. We assume further that either \( B(r) \) is strictly concave or \( L(r) \) is strictly convex.

Thus, if the release occurs in period 1, the cleanup costs are \( L(x); \) then, if there is a second release in period 2, there are additional cleanup costs equal to \( L(z). \) If there is no release at the end of period 1, but there is a release at the end of period 2, the cleanup costs are \( L(x + y). \)

Finally, there is a discount factor \( k \) that reflects the time value of money. The benefits and costs in period 2 are discounted by a factor \( k. \)

Thus,

\[
\begin{align*}
  x & = \text{amount dumped in period 1;} \\
  y & = \text{amount dumped in period 2, given no release in period 1;} \\
  z & = \text{amount dumped in period 2, given a release in period 1;} \\
  p_1 & = \text{probability of a release in period 1, or of a release in period 2, given a release in period 1;} \\
  p_2 & = \text{probability of a release in period 2, given no release in period 1; } 0 < p_1 < p_2 < 1; \\
  k & = \text{discount factor; } 0 < k \leq 1; \\
  B(r) & = \text{benefit that accrues to the actor from dumping } r; \\
  L(r) & = \text{cleanup costs for } r \text{ in the event of a release; and} \\
  \hat{x}, \hat{y}, \hat{z} & = \text{standards of care, under rules of negligence, that correspond to the choices } x, y, \text{ and } z, \text{ respectively.}
\end{align*}
\]

\[16\] All of our conclusions, however, hold even if \( p_2 \) equals \( p_1. \) In contrast, one might believe that, in some contexts, \( p_2 < p_1. \) For example, the lack of a release in a period 1 might indicate that the site has geologically desirable characteristics. Alternatively, the wastes might degrade over time. When \( p_2 < p_1, \) all our results concerning the efficiency properties of the various liability rules hold in the two-period model. Some results that describe the relationships among \( x^*, y^*, \) and \( z^* \) may not hold. The results on the relationship among \( x \) in the infinite-period model do not hold.

\[17\] We assume that there is no divergence between the private discount factor and the social discount factor.
The various possible outcomes are illustrated in Figure 1. Under outcome A, there is a release in both periods; the actor therefore causes a loss of $L(x) + L(z)$. The probability of this outcome is $p_1^2$. Under outcome B, there is a release in period 1 but no release in period 2; the actor therefore causes a loss of $L(x)$. The probability of this outcome is $p_1(1 - p_1)$. Under outcome C, there is a no release in period 1, but there is a release in period 2; the actor therefore causes a loss of $L(x + y)$. The probability of this outcome is $(1 - p_1)p_2$. Finally, under outcome D, there is no release in either period; therefore the actor does not cause any loss. The probability of this outcome is $(1 - p_1)(1 - p_2)$.

Throughout the article, we will proceed by backward induction. Thus,
we will look first at the actor’s decision in period 2, define an optimal response in period 2 for a given action in period 1, and then solve the actor’s maximization problem in period 1.

II. Strict Liability

Under strict liability, the actor is responsible for the full cleanup costs. In period 2, the actor faces the following objective function if there has been no release in period 1:

$$\max_y B(y) - p_2L(x + y).$$

If there has been a release in period 1, the objective function is

$$\max_z B(z) - p_1L(z).$$

Let $y(x)$ and $z^*$ satisfy these conditions; $y(x)$ is the optimal response in period 2 to the dumping of $x$ in period 1. Note that, if there has been no release in period 1, the choice of $y$ in period 2 is dependent on the choice of $x$ in period 1 because the actor’s liability in the event of a release is $L(x + y)$. In contrast, if there has been a release in period 1, the choice of $z$ in period 2 is independent of the choice of $x$ in period 1 because the actor’s liability in the event of a release is $L(z)$, which is not a function of $x$.

In period 1, the actor faces the following objective function:

$$\max_x B(x) - p_1L(x) + k((1 - p_1)[B(y(x)) - p_2L(x + y)]) + p_1[B(z^*) - p_1L(z^*)]).$$

The solution to this expression defines $x^*$ and $y(x^*)$; we will label the latter term as $y^*$—the optimal response in period 2 to the dumping of $x^*$ in period 1.

These objective functions show that strict liability induces the socially optimal outcome. Indeed, in each of the periods, and regardless of when a release occurs, the actor captures the full benefits of the activity but must also bear the full social loss. Thus, the actor’s private objective function is equal to the social objective function.

Turning to the relationships among $x^*$, $y^*$, and $z^*$, one can draw the following conclusions. The first conclusion is that $z^*$ is greater than...

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18 Because “negative” dumping does not have a physical interpretation, it is necessary that $x \geq 0$, $y \geq 0$, $z \geq 0$. In addition, the description of the model requires that $x > 0$. If the actor chooses not to dump at all in period 1, there can be no release at the end of this period. Thus, the actor can never face the question of how much to dump in period 2 following a release in period 1; the distinction between $y$ and $z$ loses its meaning.

Thus, we place certain constraints on the benefit and damage function to ensure that...
y*.\(^{19}\) The actor faces a smaller loss function in period 2 when there has been a release in period 1 for two reasons. In the face of such a release, the probability of a further release is \(p_1\). In the absence of a release in period 1, the probability of a release in period 2 is \(p_2\), which is greater than \(p_1\). Moreover, for a given amount of waste dumped in period 2, say \(u\), the potential liability in period 2, given that a release occurred in period 1, is \(L(u)\), whereas if no release has occurred in period 1, the potential liability in period 2 is \(L(x + u)\), which is larger. The actor derives the same benefit from a given level of dumping in period 2, regardless of whether there has been a release in period 1. Thus, the smaller loss function in period 2 when there has been a release in the period 1 leads to \(z^*\) being greater than \(y^*\).

Second, \(z^*\) is also greater than or equal to \(x^*\), with equality only if \(k = 0\).\(^ {20}\) If \(k = 0\), the actor is completely myopic; it does not consider the consequences of its actions in period 1 on its situation in period 2.\(^ {21}\) Consequently, in period 1, it acts as if it faces only a risk of \(p_1\) of a release in that period; it ignores the additional risk of \((1 - p_1)p_2\) of a release in period 2 of the waste dumped in period 1. But, given a release in period 1, the actor, in choosing \(z^*\), in fact faces only a risk of \(p_1\) of a release. Hence, the actor would dump the same amount in each period, as the sequential features of the model would disappear. But when \(k\) is positive, the actor understands that the dumping in period 1 can lead to a release at the end of period 1 with probability \(p_1\) and a release at the end of period 2 with probability \(p_2\). In contrast, the dumping in period 2, given a release in period 1, can lead only to a release at the end of period 2 with probability \(p_1\). Once again, the smaller loss function faced by the actor in period 2 when there has been a release in period 1 leads to \(z^*\) being greater than \(x^*\).

Third, the relationship between \(x^*\) and \(y^*\) is dependent on the functions \(B\) and \(L\) and the parameters \(p_1, p_2,\) and \(k\).\(^ {22}\) At first glance, it would appear that dumping in period 2 would be more desirable because it exposes the actor only to a single loss, with probability \(p_2\), rather than two losses, one with probability \(p_1\) and the other with probability \(p_2\).

This incentive to dump more in period 2 is counteracted in several

\(^{19}\) See id. at appendix, lemma 1(b).
\(^{20}\) See id. at appendix, lemma 1(a).
\(^{21}\) We do not wish to imply, however, that the actor’s private discount factor differs from the social discount factor. See note 17 supra.
\(^{22}\) See Kornhauser & Revesz, supra note 12, at appendix, lemma 2.
ways. The net benefits that accrue from dumping in period 2 must be discounted by a factor $k$, thereby creating a preference for dumping in period 1. Also, if the benefit function is strictly concave, an actor would not choose to do all of its dumping in period 2 because it would derive a greater benefit from an additional unit of dumping in a period in which it is dumping fewer units.

In addition, the convexity of the damage function and the fact that $p_2$ is greater than $p_1$ push the actor in the direction of dumping more in period 1. Assume that there is going to be a release at the end of period 2. For a given total amount of wastes dumped over the two periods, if the damage function is strictly convex, the amount paid where there is a single release at the end of period 2 will be greater than that paid where there is a release at the end of each period. Thus, the absence of a release at the end of period 1 induces the actor to dump less in period 2. This result is further exacerbated because $p_2$ is greater than $p_1$.

With one modification, the results of our model are generally consistent with a case in which the actor dumps in an infinite number of periods rather than just in two. In the two-period case, the actor faces an "end-period" in period 2 in which its current decisions have no future consequences. This consideration is most evident in the event of a release in period 1. In that instance, the actor will choose $z^*$ greater than $x^*$ because that choice exposes it to liability in one period only. But in an infinite-period problem, this result does not hold; dumping in period 2 exposes the actor to liability not only in that period but also in all subsequent periods until there is a release. Consequently, in an infinite-period model, after a release, the actor would once more choose $x^*$.

For similar reasons, when there is no release at the end of period 1, the amount dumped in period 2 will be less in the infinite-period model than in the two-period model. In the infinite-period model, the lack of a release at the end of two periods does not preclude a release in subsequent periods. Once again, the strict convexity of the damage function implies that the absence of a release at the end of one period induces the actor to dump less in the subsequent period. We show that the amount dumped starts at $x^*$ and then decreases in each period until there is a release and is $x^*$ once again in the period following a release.23

III. NEGLIGENCE

In a single-actor, single-period model, a rule of negligence is simple both to define and analyze. Under a rule of negligence, the actor is re-

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23 See id. at appendix, proposition 2. Of course, if the optimal amount dumped in a given period is zero, the actor will not dump again until after a release.
sponsible for the full social loss if it violates the standard of care. Otherwise, it is responsible for no loss at all. Moreover, when the standard of care is set at the optimal level, the actor will adopt that level.24

The extension of the model to two (or more) periods complicates not only the analysis of the model but also the definition of negligence and the assignment of appropriate standards of care. In particular, we need to draw a distinction between forgiving and unforgiving rules. The two rules assign responsibility for releases in period $t$ to an actor who is negligent in that period. They differ, however, in their treatment of actors who, though nonnegligent in period $t$, when a release occurs, were negligent in at least one period following the prior release. A forgiving rule does not assign responsibility for releases in period $t$ to an actor who is nonnegligent in that period, regardless of its prior behavior. In contrast, an unforgiving rule assigns liability to such an actor if the actor was negligent in at least one period following the prior release.

Consider, in our model, a situation in which there is no release in period 1 but there is a release in period 2 and where the actor is negligent in period 1 but nonnegligent in period 2. Under a forgiving rule, the actor would not face liability in period 2, but, under an unforgiving rule, it would face liability in period 2.

We analyze first a forgiving rule that sets the following standards of care: $\hat{x} = x^*$, $\hat{y} = y^*$, and $\hat{z} = z^*$. This rule is suggested by the single-period problem. In essence, the single-period problem is no different from a multiperiod problem in which an actor’s actions in one period have no effect on the social loss in other periods. In that case, the optimal standard of care for each period is set at the level that maximizes social welfare, and an actor is immune from liability if there is a release in a period in which it meets the standard. By analogy, one might think that where an actor’s decisions in one period have an effect on the social loss in other periods, the efficient result will be generated by a rule that sets the standards of care for each period at the socially optimal level and immunizes the actor from liability for a release in periods in which it meets those standards. We show below that despite this surface plausibility, the analogy does not hold; we then analyze two reformulations of the standards of care.

It is easy to see that, under this rule, the actor will choose $z^*$ in period

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24 If the law establishes an extremely stringent standard of care, negligence will function like strict liability and also induce the single actor to adopt the optimal level of care.

2, contingent on a release in period 1. Indeed, as we pointed out in our discussion of strict liability, the choice of $z$ in period 2 is independent of the choice of $x$ in period 1. Thus, in the event of a release in period 1, the problem the actor faces in period 2 is a single-period problem. If it chooses a level greater than $z^*$, it bears the full cost of its actions. The net benefits to the actor of this decision are less than if it chose $z^*$, the level of waste that maximizes net social welfare. Since the other rules that we analyze also induce the optimal choice of $z$, we focus the remainder of the discussion only on the choices of $x$ and $y$.

We now analyze the rule's performance with respect to the choice of $x$ and $y$. The actor faces the following objective function in period 2, given no release in period 1:

$$\max_y \begin{cases} B(y) - p_2 L(x + y), & y > y^*, \\ B(y), & y \leq y^*. \end{cases}$$

This expression shows that the actor will not be negligent in both periods. For if $x > x^*$, the $y(x)$ that maximizes $B(y) - p_2 L(x + y)$ is less than or equal to $y^*$. Thus, if the actor is negligent in period 1, it will choose $y$ equal to $y^*$ in period 2; the actor would not choose a smaller amount because it can escape all liability by choosing $y^*$. Conversely, it will choose $y$ greater than $y^*$ only if $x$ is smaller than $x^*$ in period 1.

The actor thus faces the following objective function in period 1:

$$\max_x \begin{cases} B(x) - p_1 L(x) + k(1 - p_1) B(y^*), & x > x^*, \\ B(x) + k(1 - p_1) [B(y) - p_2 L(x + y(x))], & x < x^*, \\ B(x^*) + k(1 - p_1) B(y^*), & x = x^*. \end{cases}$$

But over the range $x \leq x^*$, the expression

$$B(x) + k(1 - p_1) [B(y) - p_2 L(x + y)]$$

is maximized at $x^*$. This objective function differs from the one that arises under strict liability in that the actor does not face liability for $p_1 L(x)$, as it meets the standard of care in period 1. Thus, if the choice of $x$ were unconstrained, the actor would choose a value larger than $x^*$. But given the constraint, the actor would choose $x^*$. Hence, the actor

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25 See Kornhauser & Revesz, supra note 12, appendix, lemma 4.
26 Id. at appendix, lemma 5.
27 Id. at appendix, lemma 3(a).
28 Id. at appendix, lemma 3(b).
29 Id. at appendix, lemma 7.
will never choose an \( x \) that is smaller than \( x^* \). A corollary is that it will never be negligent in period 2 and will therefore choose to dump \( y^* \),\(^{30}\) as we have indicated that it will choose \( y \) greater than \( y^* \) only if it chose an \( x \) smaller than \( x^* \).

Note, however, that for some functions \( B \) and \( L \), the actor will dump more than \( x^* \) in the period 1 but for other functions will dump \( x^* \).\(^{31}\) If the actor is negligent in period 1, the level of dumping that maximizes its objective function is greater than \( x^* \). In contrast to the objective function that the actor faces under strict liability, here it is not responsible for the expected damage associated with the period 2 discharge, which is \( k(1 - p_1)p_2 L(x + y) \). For some functions, the actor will prefer to dump at this higher level and be liable for the expected damage \( p_1 L(x) \) rather than dump at \( x^* \) and be exempted from this liability.

In summary, the rule in which the optimal standard of care for each period is set at a level that maximizes social welfare in that period but does not consider social welfare in subsequent periods fails to create the correct incentives because, when no release occurs in period 1, it permits the actor to escape the consequences of its negligence in this period.

This underdeterrence is not a product of an end-period problem. It exists as well in the infinite-period problem, where an actor can avoid the consequences of a violation of the standard of care in any period in which there is no release, even though the violation has consequences in subsequent periods.\(^ {32} \)

This underdeterrence can be corrected by means of an unforgiving rule. Consider such a rule with the standards of care set, once again, at \( \hat{x} = x^* \), \( \hat{y} = y^* \), and \( \hat{z} = z^* \). Now, if the actor dumps an amount greater than \( x^* \) in period 1 but there is no release in that period, the actor will be liable for a release in period 2, even if it meets the standard of care in this period by dumping \( y^* \).

This unforgiving rule is suggested by the literature on sequential decisions by two actors, each operating in one period.\(^ {33} \) For example, under

\( \text{Id. at appendix, lemma 6.} \)

\( \text{Id. at appendix, proposition 1. In contrast, a partial liability rule always produces underdeterrence in period 1, regardless of the functions } B \text{ and } L. \)

\( \text{Id. at appendix, lemma 13.} \)


The models in these articles adopt \( \hat{y} = y(x) \) as the "second-period" standard of care.
a rule of negligence with contributory negligence, if an injurer acts first and violates the applicable standard of care, and the victim acts next and meets the standard of care, the injurer is liable for the full loss, even for the portion attributable to the victim. Here, under an unforgiving rule, if the actor violates the standard of care in period 1 but meets it in period 2, and the release occurs in period 2, the actor is liable for the full social loss, even for the portion of the social loss attributable to actions in period 2.

Under this unforgiving rule, instead of function (1), the actor faces the following objective function in period 1, for $x > x^*$:

$$B(x) - p_1L(x) + k(1 - p_1)[B(y^*) - p_2L(x + y^*)].$$

This function is identical to the function that the actor faces under strict liability and is therefore maximized at $x^*$, rather than at a level higher than $x^*$. Moreover, if the actor chooses $x^*$ in period 1, it receives, in fact, the greater net benefits of function (3), namely,

$$B(x^*) + k(1 - p_1)B(y^*).$$

Thus, this unforgiving rule corrects the flaw of its forgiving counterpart and induces the actor to choose $(x^*, y^*, z^*)$. The unforgiving rule produces the socially optimal results in the infinite-period problem as well.34

While the unforgiving rule with the standards of care set at the socially optimal level in each period leads to the efficient outcome, it has some troubling features. Suppose, for example, that the actor is negligent in period 1 and generates a level $x = (x^* + \epsilon)$ of waste. Suppose further that no release occurs in period 1 and that, in period 2, not only is the actor nonnegligent but it compensates for its prior negligence in period 1 by generating $y = (y^* - \epsilon)$. Thus, by the end of period 2, the actor has

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For a discussion of this standard of care in the context of a single actor operating in two periods, see note 43 infra.

Our model differs in two important respects from these models of sequential decisions by two actors each operating in one period. First, in the two-actor model, the accident can occur only after both parties have acted, while in our model it may occur either in period 1 or in period 2. Put differently, in the two-actor model, the first actor creates a dangerous condition that cannot result in an accident without the subsequent action of the other party. In our model, the accident may occur even if no second actor ever appears. Second, in our model, the actor may, under some rules, choose to cure its negligence in period 1. In contrast, in the two-actor model, no action by the second actor will insulate a negligent first actor from liability.

34 See Kornhauser & Revesz, supra note 12, appendix, lemma 14. A partial-liability, unforgiving rule with the same standards of care would also induce the efficient outcome. Under such a rule, the actor is responsible only for the cleanup cost attributable to the excess amount of waste dumped in period 1, which is $L(x + y^*) - L(x^* + y^*)$. 
generated the optimal amount of waste: \(x^* + y^*\). The unforgiving rule will still not absolve the actor of responsibility for a release in period 2. In contrast, if the actor had dumped \(x^*\) in period 1 and \(y^*\) in period 2, it would not have been liable, even though the aggregate amount dumped would have been the same. In fact, the unforgiving rule would not absolve the actor of liability even if it dumped \(y - 2\varepsilon\) (or, for that matter, \(y - 10\varepsilon\)) in period 2. This result may seem unfair because no amount of redemption in subsequent periods can cure the original negligence.

We might explain this sense of unfairness as follows: an unforgiving rule imposes liability regardless of whether the actor’s negligence is the proximate cause of the damage.\(^{35}\) In our example, by the time the release occurs, the actor has cured its initial negligence. The resulting loss in period 2 equals the loss that would have occurred had the actor met the standard of care in both periods.\(^{36}\) The actor’s initial negligence caused no additional damage.\(^{37}\)

The unfairness of unforgiving rules is exacerbated in a model with more than two periods. For example, the actor might dump \((x^* + \varepsilon)\) in period 1, \((y^* - \varepsilon)\) in period 2, and then meet the standard of care, say, for the next eighteen periods. At the end of period 20, the first release might occur. The actor would be liable for the release even though the effects of its negligence would have been cured many periods earlier, and this

\(^{35}\) The sense of unfairness has two related sources. First, if an observer restricts attention to period 2, the two cases are “alike,” but they are treated differently. Of course, the actor behaved differently in period 1 in the two cases; moreover that difference has different incentive effects on the actor that, from an economic perspective, justify the different treatment in period 2. For a more extensive discussion of the problems in the idea of “equivalent cases,” see Lewis A. Kornhauser, An Economic Perspective on Stare Decisis, 65 Chi.-Kent L. Rev. 63 (1989).

Second, economic models of negligence do not adequately capture the legal concept of a standard of care. In our model, the actor’s negligence in period 1 is intentional when, in reality, it may have been inadvertent. Thus, the actor may have tried to meet the standard but, “through no fault of its own,” failed. If it then compensates for its period 1 error by restricting output in period 2, the unforgiving rule seems overly harsh.

\(^{36}\) One might make a similar causal objection to full-liability rules in the single-period context, where a negligent actor pays the full costs of an accident, not just the costs attributable to the negligence. See note 14 supra. But in this single-period problem, the full costs of the accident are greater than they would be if the actor had been nonnegligent.

\(^{37}\) Note, however, that if an actor fails to cure its initial negligence, that negligence does cause additional damage. Suppose, for example, that the actor negligently chooses to dump \(x > x^*\) in period 1 but meets the standard of care \(y^*\) in period 2. Then its negligence causes additional damage of \(L(x + y^*) - L(x^* + y^*)\).

The problem would be more complex if the initial negligent act of dumping \((x^* + \varepsilon)\) increased the probability of a release in period 2 even when the actor dumped \(y \leq (y^* - \varepsilon)\) in period 2. In this case, the reduced dumping in period 2 does not fully cure the prior negligence.
negligence would therefore have been of no continuing social consequence.38 This effect is common to all unforgiving negligence rules.

The example highlights a second, general problem of unforgiving negligence rules. If the actor is negligent in one period, in all subsequent periods before a release the rule is, in effect, a strict liability rule. Indeed, regardless of what the actor does in the periods following its initial negligence, it will be liable for a release. Given that strict liability induces the efficient response, it is not surprising that the unforgiving rule does so as well. But, in some sense, it can be seen as not being a true negligence rule, and, to the extent that one prefers a rule of negligence over one of strict liability, there is reason to dislike it.

A third problem with an unforgiving negligence rule draws on our prior analysis of two infinitely solvent actors in a single period, which showed that strict liability induced underdeterrence.39 Plausibly, a similar problem might arise under an unforgiving rule. Suppose the actors dump over many periods and, early on, at least two actors inadvertently exceed their standard of care. During the period between the initial negligence and the time of the first release, these actors face a rule of strict liability that presumably offers socially undesirable incentives.40

We therefore search for a forgiving rule that induces the socially optimal outcome. The causal objection to unforgiving rules suggests the appropriate formulation of the standard of care in a forgiving rule: set the standard of care in period 2, contingent on no release in period 1, so that

38 The timing of the negligence and its cures are irrelevant. Suppose there are three periods with \( w = \hat{w} - \epsilon/2 = w^* - \epsilon/2 \) in period 0, \( x = \hat{x} + \epsilon = x^* + \epsilon \) in period 1, and \( y = \hat{y} - \epsilon/2 = y^* - \epsilon/2 \) in period 2. If a release occurs in period 2, the period 1 negligence has caused no additional damage and hence seems harmless. (Of course if a release occurred in period 1, the negligence was harmful because the total amount dumped \( w + x = w^* + x^* + \epsilon/2 \) exceeds the social optimum by \( \epsilon/2 \).)

39 See Kornhauser & Revesz, supra note 6, at 856–58.

40 In multiple-tortfeasor, multiple-period situations, it appears not to be possible to draw any general conclusions on the relative desirability of the forgiving negligence rule discussed above and a strict liability rule. The relative desirability of the rules appears to depend on the functional forms defining the benefits that the actors derive from the activity and the costs that they impose on society.

In multiple-tortfeasor, single-period situations, negligence is superior to strict liability, but in single-tortfeasor, multiple-period situations, strict liability is preferable to a forgiving negligence rule with standards of care set at \( x^* \) and \( y^* \). We have not formally modeled the problem, but the penalties of each of the rules—that is, the departures from the social optimum—are dependent on the functional forms.

There is ambiguity, also, in the relative desirability of forgiving and unforgiving negligence rules in multiple-tortfeasor, multiple-period situations when the standards of care are set at \( x^* \) and \( y^* \). The forgiving negligence rule appears preferable from a multiple-tortfeasor perspective (because it does not converge to strict liability), but, as we have shown, it is less desirable from a multiple-period perspective.
it is violated if and only if the total amount dumped in periods 1 and 2 is greater than \( x^* + y^* \). Thus, \( \dot{x} = x^*; \dot{y} = c(x) = x^* + y^* - x; \ z = z^* \).41

Under this rule, the actor will meet the standard of care in period 2. It will dump no less than the amount permitted by the standard of care because, until it exceeds the standard, additional waste imposes no additional cost on it.

To understand why it will not dump more than \( \dot{y} \), we must consider two cases. Recall, from the discussion of strict liability, that if the actor faces liability in period 2, its optimal response to the dumping of \( x \) in period 1 is \( y(x) \). If, in period 1, the actor chose \( x < x^* \) and hence was nonnegligent, its optimal response, if it faced liability in period 2, would be \( y(x) > y^* \). But, for \( x < x^* \), it follows that \( x + y(x) < x^* + y^* \).42 Thus, if the actor chose to be nonnegligent in period 1, it would choose to dump less than \( c(x) \) in period 2 even if it faced liability in period 2. It follows, a fortiori, that it will choose to dump no more than \( c(x) \) where this choice exempts it from liability.

If, in contrast, the actor chooses to dump more than \( x^* \) in period 1, it will not choose to be negligent in period 2 as well. We know from the analysis of strict liability that, if the actor is responsible for the full social loss, it will choose to dump \( x^* \) and \( y^* \) rather than larger amounts.

Consider now the actor’s choice in period 1. We have established that, if the actor dumps more than \( x^* \) in period 1, it will have to dump less than \( y^* \) in order not to violate the standard of care in period 2. Indeed, because \( x + y(x) > x^* + y^* \) for \( x > x^* \), the actor will have to dump \( y < y(x) \) in order to avoid violating the standard of care in period 2. This restriction removes the incentive the actor had under the forgiving rule with standards of care set at \( x^* \) and \( y^* \) to be negligent in period 1.43 Nor

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41 If the actor dumps more than \( (x^* + y^*) \) in period 1, the standard of care in period 2 is negative. Thus, regardless of how much the actor dumps in period 2, even if it dumps nothing at all, it will have violated the standard of care.

42 See Kornhauser & Revesz, supra note 12, appendix, lemma 3(b).

43 Id. at appendix, lemma 8. The restriction that \( \dot{y} = c(x) < y(x) \) for \( x > x^* \) is necessary to remove the incentive.

Another plausible, forgiving rule would set \( \dot{y} = y(x) \). In a two-actor model, if the first actor violates the standard of care, the standard for the second actor is set at the optimal response to the first actor’s choice. This standard is more stringent than the optimal standard where the first actor is nonnegligent. See Wittman, supra note 33.

In our one-actor, two-period model, if \( \dot{x} = x^* \) and \( \dot{y} = y(x) \), an incentive for negligence in period 1 would remain. That is, for some functions \( B \) and \( L \), the actor will prefer to dump at a level higher than \( x^* \) and be liable for the expected damage \( p_iL(x) \) as well as for the “penalty” that attaches in period 2. For other functions, it will prefer to dump at \( x^* \).

This underdeterrence could be corrected by making the rule unforgiving. Such a rule, however, would share all of the negative characteristics of the unforgiving rule discussed...
does the actor have an incentive to choose \( x < x^* \) in period 1. If the actor is nonnegligent in both periods, it faces the objective function

\[
\max_x B(x) + k(1 - \rho_i)B(x^* + y^* - x), \quad x \leq x^*,
\]

which is maximized at \( x^* \).\(^{44}\)

Thus, this forgiving rule, like the unforgiving rule discussed above, will lead to the maximization of social welfare.\(^{45}\) It will do so, however, without raising the potential negative effects of unforgiveness. Perhaps most important, it is a true negligence rule.

In terms of the information that a court must have in order to adjudicate claims, the two rules do not differ significantly; to the extent that they do differ, however, the unforgiving rule is somewhat more parsimonious. Two potential differences arise when the first release occurs in period 2. First, under the unforgiving rule, once a court determines that the actor violated the standard of care in period 1, it does not need to ascertain the level of dumping or the standard of care in period 2. Regardless of what the actor does in this period, it will be liable. In contrast, under the forgiving rule, the court will need to ascertain the actor’s dumping in period 2 in order to determine whether the aggregate amount dumped is greater than \( (x^* + y^*) \). Second, once a court determines that the actor has violated the standard of care in period 1, it does not need to determine the extent of the violation, as this information would have no legal significance.

In contrast, under the forgiving rule, the extent of the violation is relevant to determine whether the aggregate amount dumped is greater than \( (x^* + y^*) \).

\(^{44}\) See Kornhauser & Revesz, supra note 12, appendix, lemma 9. A partial liability, forgiving rule with the same standards of care would also induce the efficient outcome.

\(^{45}\) We believe, but have not proven, that this result also holds in the infinite-period problem.
IV. Conclusion

We show that strict liability induces the socially optimal outcome. The analysis of negligence is more complex because of the multiplicity of plausible negligence rules. Out of the three such rules we discuss, only the rule in which the standard of care is set at the socially optimal level for period 1, but in which the actor faces no liability for releases in period 2 that result from negligence in period 1, produces underdeterrence. The other two rules severally produce the optimal level of deterrence across both periods but have different characteristics. Most important, one is forgiving whereas the other is unforgiving. We explain that the forgiving rule is a more traditional negligence rule but that the unforgiving rule may impose somewhat lesser informational burdens on courts.